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Research papers

Strongly heterogeneous patterns of groundwater depletion in Northwestern India

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A R T I C L E I N F O

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A B S T R A C T

Northwestern India has been identified as a significant hotspot of groundwater depletion, with major implications for groundwater sustainability caused by excessive abstraction. We know relatively little about the detailed spatial and temporal changes in groundwater storage in this region, nor do we understand the interplay of factors controlling these changes. Groundwater managers and policymakers in India require such information to monitor groundwater development and make strategic decisions for the sustainable management of groundwater. Here, we characterise high-resolution spatio-temporal variability in groundwater levels and storage change across northwestern India through analysis of *in situ* measurements of historical groundwater level data. We note a slow gain in groundwater storage of $+ 0.58 \pm 0.35$ km^3 for the pre-monsoon and $+ 0.40 \pm 0.35$ km^3 for the post-monsoon period between 1974 and 2001. However, from 2002 to 2010, groundwater storage was rapidly depleted by -32.30 ± 0.34 km^3 in the pre-monsoon and -24.42 ± 0.34 km^3 in the post-monsoon period. Importantly, we observe marked spatial heterogeneity in groundwater levels and storage change and distinct hotspots of groundwater depletion with lateral length scales of tens of kilometers. Spatial variability in groundwater abstraction partially explains the depletion pattern, but we also find that the sedimentological heterogeneity of the aquifer system correlates broadly with long-term patterns of groundwater-level change. This correlation, along with the spatial agreement between groundwater level change and water quality, provides a framework for anticipating future depletion patterns and guiding groundwater monitoring and domain-specific management strategies.

1. Introduction

India is the largest user of groundwater in the world. Total annual groundwater abstraction in India was estimated to be about 245 km^3 in 2011 (CGWB, 2014a), out of which about 90% was consumed for irrigation (Saha et al., 2018). This high usage defines the groundwater irrigation economy on which India's national food security depends (Hira, 2009; Shankar et al., 2011; Smilovic et al., 2015; Zaveri et al., 2016; Cao and Roy, 2020). Groundwater-fed irrigation is especially crucial for sustaining the agricultural economy of the Indo-Gangetic basin. The alluvial aquifer system that infills this basin is one of the world's most important freshwater resources (MacDonald et al., 2016) and accounts for a significant proportion of the world's total groundwater abstraction (Wada et al., 2010). Expansion of irrigated agriculture and increased reliance on groundwater abstraction for irrigation has led to marked exploitation of this aquifer system, thus threatening the sustainability of the aquifer and agricultural productivity for current and future generations (Gleeson et al., 2020). This is particularly true of the aquifer system in the northwestern states of Punjab and Haryana (Fig. 1a–d), which has been identified as a major hotspot of groundwater depletion at a global scale (Rodell et al., 2009; MacDonald et al., 2016). The alluvial aquifers underlying the Indo-Gangetic basin in this

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intensively cultivated region are heavily exploited for groundwater and are used for 62% of regional irrigation, 50% of urban water supply, and 85% of rural water supply (Siebert et al., 2010; Shankar et al., 2011; Saha et al., 2018). Rates of groundwater abstraction in the states of Punjab and Haryana, which make up the leading agricultural region of India, have risen sharply since the mid-20th century to support a massive increase in agricultural productivity, termed the "Green Revolution," which was aimed at achieving self-sufficiency in food production. Annual food grain production increased four-fold from 50 million tons in 1950–51 to 203 million tons in 1999–2000 (Kumar et al., 2005). In addition, since 1970, farmers have shifted from low water-consuming crops such as maize, pearl millet, pulses, and oilseeds to water-hungry paddy cultivation (e.g., Davis et al., 2018). This shift was accompanied by a rapid increase in the number of tube wells in northwest India, from ~ 0.1 million in 1960 to ~ 1.27 million in 2008 (Hira and Khera, 2000; Sharma et al., 2008; Mishra et al., 2018). The increase in groundwater-fed irrigation has been aided by the provision of electricity for pumping at subsidised rates (Badiani et al., 2012). The Green Revolution has been cited as the primary cause behind the dramatic fall in groundwater levels in the region through uncontrolled pumping and groundwater abstraction (Zaveri et al., 2016). Detailed data on tube well locations and abstraction rates are not routinely collected, however, and until the last decade, the true magnitude and extent of the resulting groundwater depletion at the regional scale have been poorly constrained.

Within the last ten years, strong evidence for excessive regional-scale groundwater depletion encompassing the states of Punjab, Haryana and Rajasthan has been derived from Gravity Recovery and Climate Experiment (GRACE) satellite gravimetry. For example, Rodell et al. (2018) estimated the rate of total water storage loss in northern India at −19.2 ± 1.1 km^3/year, which is similar to previous GRACE-based estimates (Rodell et al., 2009; Tiwari et al., 2009; Chen et al., 2014; Panda and Wahr, 2015; Long et al., 2016). Asoka et al. (2017) estimated a decline of −2 cm/year in groundwater storage of northern India between 2002 and 2013, as derived from GRACE data in combination with *in situ* measurements from groundwater observation wells, and compared the relative impacts of abstraction and rainfall in determining storage change and recharge. The applicability of GRACE to the assessment of regional-scale groundwater storage variation, however, and its utility for groundwater management and governance, are constrained by its low spatial resolution (Yeh et al., 2006; Scanlon et al., 2012; Alley and Konikow, 2015; Miro and Famiglietti, 2018). GRACE studies show the whole of northwestern India to be a region of high groundwater depletion, but the low spatial resolution of GRACE observations likely masks important spatial variability in groundwater storage change (Alley and Konikow, 2015; MacDonald et al., 2016) that arise as a consequence of variability in aquifer properties and/or abstraction patterns. GRACE observations are also limited to 2002-onwards, again precluding the identification or analysis of multi-decadal trends (e.g., Asoka et al., 2017; Asoka and Mishra, 2020).

Given these issues with satellite-derived gravimetric data, groundwater level variability is traditionally monitored through *in situ* measurements of groundwater level from observation wells, although such data are often sparse, irregularly distributed, and poorly integrated across political boundaries (Bierkens and Wada, 2019). Numerous studies have investigated the spatio-temporal variability of groundwater storage across India using *in situ* measurements (Bhanja et al., 2017; Asoka et al., 2018; Mishra et al., 2018; Sinha et al., 2019; Asoka and Mishra, 2020; Shekhar et al., 2020; van Dijk et al., 2020; Dangar et al., 2021; Joshi et al., 2021; Tiwar et al., 2021), but their data density across northwestern India was limited (e.g., see Fig. 1 of Bhanja et al., 2017, and Fig. 1b of Asoka and Mishra, 2020). Asoka et al. (2018) and Asoka and Mishra (2020) reported a significant lowering of the water table during 1996–2013 in the majority of observation wells in northern

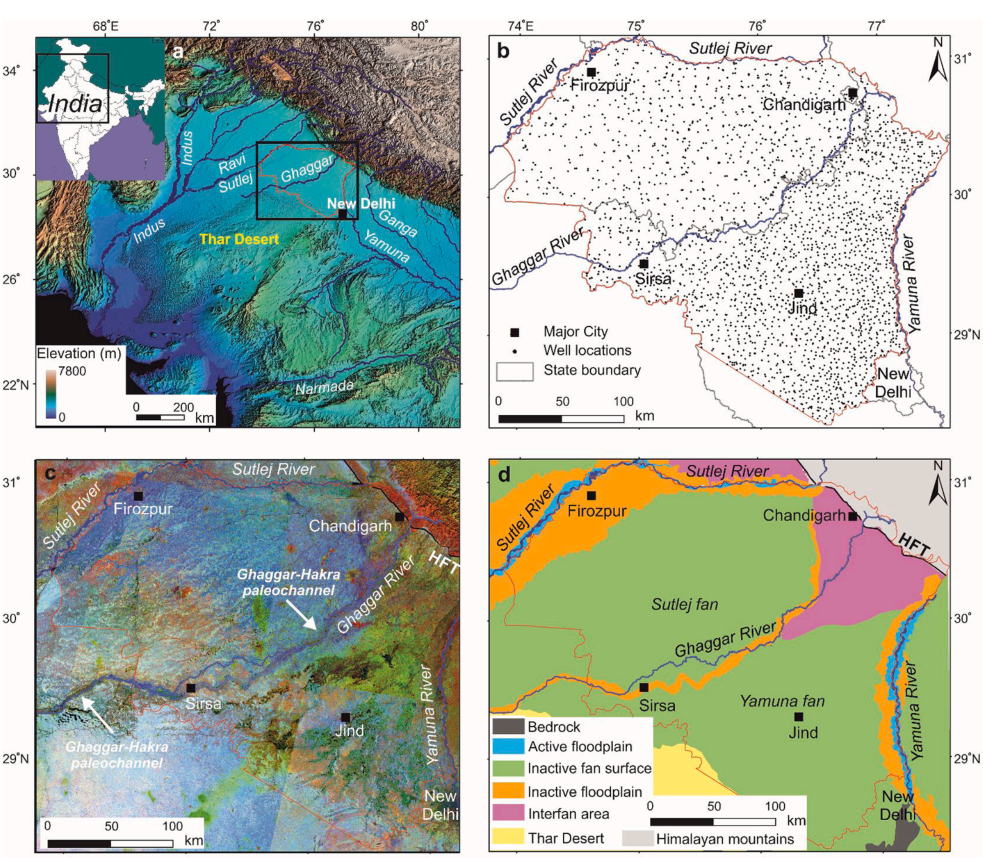

Fig. 1. Overview of the study area. (a) Surface topography of northwestern India and Pakistan derived from NASA Shuttle Radar Topographic Mission (SRTM) digital elevation model. Blue lines show major rivers and red line shows the outline of the Sutlej-Yamuna plains in northwest India. Black box shows the area covered in panel b–d. (b) Groundwater monitoring wells locations in the study area. Black lines show state borders. (c) Colour composite image of Landsat 5 bands 4, 5 and 6 (RGB). Dark blue colours indicate zones of high soil moisture near the Ghaggar River associated with the Ghaggar-Hakra paleochannel (Yashpal et al., 1980; Singh et al., 2017). (d) Geomorphic map of the study area modified from van Dijk et al. (2016a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

India, but the low density of well records in their dataset precludes fine-scale evaluation of spatial variation in groundwater levels in this region. In one of the few large-scale *in situ* studies to date in northern India, MacDonald et al. (2016) mapped groundwater depletion across the entire Indo-Gangetic basin. They showed a depletion rate of -2.6 ± 0.9 km^3/year for Punjab and -1.4 ± 0.5 km^3/year for Haryana between 2002 and 2012 (MacDonald et al., 2016). Again, however, the spatial density of their historical *in situ* measurements from groundwater observation wells in northwestern India was relatively low. In addition, the 11-year window spanned by their data made it impossible to assess multi-decadal trends, due for example to changing patterns of agricultural land use. More recently, Asoka et al. (2018) used data from more than 5800 wells across India to examine the relationship between rainfall intensity and groundwater recharge. They concluded that low-intensity monsoon rainfall dominates recharge in northwestern India, although these results are based on a fairly small subset of only 139 wells.

Thus, despite considerable progress, current observations, both *in situ* and satellite-borne, do not permit quantification of the spatio-temporal pattern of groundwater level variability and storage change at a resolution useful for effective groundwater resource management. In the case of *in situ* observations, a high-density network of observation wells is required to monitor changes and target interventions. Moreover, it has not yet been possible to identify the relative importance of environmental, geological, or anthropogenic factors that influence the water table. This is a critical shortcoming because such information is needed to support policies for sustainable groundwater resource management (Milman and MacDonald, 2020) and to prevent damage to long-term agricultural production. If unchecked, continued depletion of groundwater in the region may lead to future agricultural decline (Aeschbach-Hertig and Gleeson, 2012) with associated socio-economic impacts (Barik et al., 2017).

This paper aims to characterise and quantify the detailed spatio-temporal patterns of groundwater level variability using *in situ* data from across northwestern India, and to evaluate the factors governing the widely reported trend of anthropogenic groundwater depletion in this region. Our specific objectives are: (1) to characterize the spatio-temporal variation in groundwater level trends and their degree of clustering, (2) to quantify groundwater storage changes between 1974 and 2010, and (3) to evaluate the factors that may control the detailed patterns of groundwater level changes in the region and the potential implications for groundwater resource management and governance. Our analysis covers a period of c. forty years since 1974 and at a considerably finer spatial resolution than has been achieved by either GRACE observations or the basin-scale analyses of MacDonald et al. (2016) and Asoka et al. (2018). We have integrated groundwater level measurements from a dense network of 4417 observation wells across northwestern India. Our dataset combines, for the first time, twice-yearly (pre- and post-monsoon) groundwater level measurements from two different sources, the Central Groundwater Board (CGWB) of India and the state groundwater boards of Punjab and Haryana, into a common spatial framework.

2. Geomorphology and hydrogeology of the study area

2.1. Sediment routing systems

The focus of our study is the northwestern Indian aquifer system that underlies the Indo-Gangetic plains and is comprised of alluvial deposits of the Himalayan foreland basin. Observations of satellite imagery and digital elevation models have enabled the detailed characterisation of the sediment routing systems and geomorphology of the study area, which are pertinent to understanding this aquifer system. These sediment routing systems comprise two major fluvial depositional fans formed by the Sutlej and Yamuna rivers (Geddes, 1960; van Dijk et al., 2016a; Singh et al., 2017). The fans form relatively simple conical shapes with their apices located at the outlets of the Sutlej and Yamuna rivers at the Himalayan mountain front. The northern boundary of the fan deposits is defined by the Himalayan Frontal Thrust (HFT). At their distal southern and southwestern boundaries, fan deposits are bounded by the crystalline basement of the Indian craton and eolian deposits of the Thar desert, respectively. Both the Sutlej and Yamuna rivers are currently incised by up to 20 m into older fan deposits and flow in large, incised valley systems, such that the fan surfaces are largely inactive alluvial surfaces that are disconnected from modern Himalayan river flow (Singh et al., 2017). In their proximal reaches, the fans are separated by a triangular interfan area of 4000 km^2 that lies adjacent to the mountain front. This interfan area does not receive sediments from the Sutlej or Yamuna rivers but was instead formed by sediments transported from smaller rivers fed from the foothills, such as the Ghaggar River (Geddes, 1960; van Dijk et al., 2016a). In their medial and distal reaches, the lateral margins of the fans are bounded and separated by a major sinuous paleo-incised valley, the Ghaggar-Hakra paleochannel, that was formed and once occupied by the Sutlej River (Singh et al., 2017), but which now contains the Ghaggar River. The Ghaggar is a seasonal river which is sourced from the frontal Himalaya and flows southwesterly for ~ 450 km along the interfluve between the Sutlej and Yamuna fan systems before terminating in the Thar desert in Cholistan, Pakistan.

2.2. Hydrogeology

In the Himalayan foothills to the north of the Indo-Gangetic basin, groundwater resources are limited to local and shallow aquifers consisting largely of unconsolidated sediment and recharged by local rainfall (Mehta and Adyalkar, 1962). Groundwater levels in this region are typically >30 m below ground level (bgl), transmissivity ranges from 500 to 5000 m^2/day, and specific yield ranges from 10 to 26% (UNDP, 1985).

The subsurface geological heterogeneity of the alluvial aquifer system in the foreland basin is a product of the surface depositional mosaic formed by sediment routing systems at the surface and the depositional architecture of the resulting stratigraphy. Deposition of sediments in the Sutlej and Yamuna fans, and the interfan area, has created the major aquifer systems in the study area and has determined the thickness, stacking pattern, and connectivity of individual aquifer bodies (sands) separated by non-aquifer material that is predominantly silt and clay (van Dijk et al., 2016b). These aquifer bodies are narrow, 'ribbon-like' sand deposits that mark former river channel-belt positions, with individual thicknesses of up to a few 10 s of meters and widths of up to a few kilometers (van Dijk et al., 2016a). Beneath the Sutlej and Yamuna fans, these deposits form thick, abundant multi-story sand bodies with good vertical connectivity (Singh et al., 2017) but poor apparent lateral connectivity (van Dijk et al., 2016a). Thick multi-storey sand bodies occur in both proximal and distal parts of the Sutlej and Yamuna fan stratigraphy, but make up a smaller proportion of the subsurface in distal settings (van Dijk et al., 2016a). Thick multi-storey sand bodies also underlie the Ghaggar-Hakra paleochannel along the boundary between the Sutlej and Yamuna fans (Fig. 1c,d). In contrast, the interfan area is characterised by thinner and less abundant aquifer bodies in the subsurface (van Dijk et al., 2016a).

2.3. Regional climate

In July-September, the Indian Summer Monsoon (ISM) contributes approximately ~ 85% of the region's total annual rainfall, with the remainder falling in December-March (UNDP, 1985; Rajeevan and McPhaden, 2004; CGWB, 2011a; Sehgal et al., 2013). Maximum rainfall occurs over the Himalayan foothills and rainfall decreases southwards (Yadav et al., 2012). The rainfall variability has increased during the last three decades, with more frequent excess and deficient rainfall years compared to earlier periods (Mukherjee et al., 2015). The overall climate is semi-arid to subtropical, with average monthly minimum and maximum temperatures varying between 25 °C and 48 °C in summer and from 5 °C to 19 °C in winter (Kumar et al., 2014).

3. Data and methods

We compiled a database containing groundwater level records from 4071 wells maintained by state government groundwater boards between 1973 and 2012, together with 1632 CGWB well records spanning 2002 to 2013 across Punjab and Haryana. Groundwater levels were measured twice a year in June and October by the state groundwater boards, and four times a year (January, May, August, and November) by the CGWB. Given the large size of the study area, this is the most comprehensive groundwater level data set available at such a regional scale. We cleaned and filtered the groundwater level data to check their continuity in terms of a long-term record (see Supplementary Information for full details of the methodology). In particular, the data were filtered to separate continuous records (>5 years of unbroken measurements). After the rejection of duplicate or inconsistent records, the final database contained measurements from 4417 wells, which collectively span 1974 to 2010 (Fig. 1b).

We mapped changes in groundwater levels over time by interpolating individual well records across the study area, using a geostatistical kriging interpolation technique in ArcGIS, to produce groundwater level surfaces with a gridded spatial resolution of 1.5 × 1.5 km that record water levels at 5-yearly intervals from 1974 to 1999, and at yearly intervals from 2001 to 2010, for both pre-monsoon and post-monsoon seasons (see Supplementary Information for details). Since not all of the 4417 well records were continuous for the entire period, the interpolation was based on a moving subset of records for each time interval; the size of this subset ranged from 550 wells (1974) to 2007 wells (2010). We also estimated the uncertainty associated with interpolated groundwater level surface during the study period (see Supplementary Information for details). To study the temporal variation of groundwater levels, we conducted a time-series analysis of pre-monsoon groundwater level data from a subset of wells with continuous, unbroken observation records. Of the 4417 wells in our database, only 73 have continuous records from 1974 to 2010; thus, we split our analysis into continuous records covering two distinct time intervals: (a) 1974–2001 ($n = 98$) derived from the state groundwater board records, and (b) 2002–2010 ($n = 1421$) derived from both state and CGWB records. To extract trends and rates of water-level change from the time-series data, we applied the l_1 trend filtering approach of Kim et al. (2009), which generates piecewise linear trend estimates of groundwater level variation (see Supplementary Information for details).

Whilst trend analysis enables us to identify variation in groundwater levels across the study area, it does not enable easy identification of groupings of wells with similar characteristics. To detect such groupings, we used hierarchical cluster analysis to collate the time series variations of the groundwater level records into groups with similar trend characteristics (de Brito Neto et al., 2016). Cluster analysis is a widely used approach to identify similar groupings of records in long-term multivariate data (Hand et al., 2001; de Brito Neto et al., 2016; Clubb et al., 2019). We used a hierarchical clustering (HC) approach that orders the well records as a matrix, in which the rows consist of individual well records and the columns consist of water-level measurements over time. Records were progressively merged into clusters based on the dissimilarity matrix and using a Euclidean distance function. A major advantage of the HC technique is that it requires no *a priori* assumptions of the forcing functions and it preserves information on how clusters are related to each other. The proximity between rows in the final ordered matrix indicates the degree of similarity between different well records, and the degree of grouping is denoted by a hierarchical cluster tree or dendrogram (de Brito Neto et al., 2016). As with the trend analysis, we applied the cluster analysis separately to the continuous records over the periods 1974–2001 ($n = 98$) and 2002–2010 ($n = 1421$).

We then used the gridded water-level data to estimate changes in regional groundwater storage over the period 1974–2010. Groundwater level changes were converted into groundwater storage changes by multiplying the interpolated water-level changes by the estimated specific yield of the aquifers on a cell-by-cell basis:

$$\Delta G_i = \Delta h_i \times A_i \times S_{yi} \tag{1}$$

where ΔG_i is the groundwater storage change in grid cell i (in units of m^3), Δh_i is the change in water level over the specified period in that grid cell (in m); A_i is the area of the grid cell (in m^2), and S_{yi} is the specific yield of the unconfined aquifer in that grid cell. We defined the spatial pattern of specific yield (Fig. S2) from data in UNDP (1985) and CGWB (2009, 2012). Total groundwater storage change was then derived by summing the cell-wise storage changes over the entire study area.

This approach assumes unconfined conditions across the aquifer system. For this analysis, we have considered the aquifer to be unconfined based on (a) long-duration pumping test data showing the classical delayed yield associated with unconfined conditions (UNDP, 1985), and (b) isotopic signatures of groundwater samples that match with those of the recent rainfall (Lapworth et al., 2017; Joshi et al., 2018, 2020; Semwal et al., 2020). Shekhar et al. (2020) modelled groundwater level variations across the study area, assuming unconfined conditions. They showed that a calibrated and validated model with spatially-uniform but anisotropic permeabilities yielded good fits to observed water-level data across the region. These observations suggest that the aquifer system of northwestern India acts as a vertically hydraulically connected system.

To understand potential controls on groundwater level and storage changes, we compiled all available district-level data on tube well numbers and groundwater abstraction totals from the CGWB (Table S4). The number of tube wells per district is available only for 2006–2007 via the Minor Irrigation Census carried out by the Ministry of Water Resources (MoWR, 2007), and these estimates were used to calculate district-wise tube well density in units of wells per km^2. Maps of district-wise estimated groundwater abstraction totals are available only for the years 2004, 2009, and 2011 (CGWB, 2006, 2011a, 2014a). We are not aware of other direct estimates of groundwater abstraction or pumping rates across the whole of the study region at sufficiently high spatial or temporal resolution for our analysis. As an example, to overcome this limitation Asoka et al. (2017) used a standardised abstraction index estimated from a global water-balance model, while van Dijk et al. (2020) used a gridded water-deficit approach as an indirect proxy for monthly groundwater abstraction. The gridded water-deficit approach of van Dijk et al. (2020) used the soil water balance model (WaSim) of Hess et al. (2000) and India-wide annual land use maps produced by Moulds (2016) for the period 1951 to 2010. The model outcomes were calibrated against the district-wise estimated groundwater abstraction totals for the year 2011 and showed comparable spatial variation in groundwater abstraction rates to the values estimated by the CGWB. This provides some confidence in the extrapolation and use of the district-level estimates, and we use them here as the best and most direct available metrics for the spatial variability in groundwater abstraction.

To understand the relationship between groundwater level changes and climate variables, the available annual time-series data of rainfall was analyzed using the non-parametric Mann-Kendall trend test, which is extensively used to detect trends in hydroclimatic studies (Hirsch and Slack, 1984; Yue et al., 2002; Dorigo et al., 2012; Asfaw et al., 2018). Here, we used the Mann-Kendall trend test of annually and seasonally (monsoon, JJASON, and non-monsoon, DJFMAM) rainfall data obtained from Indian Meteorological Department (IMD) Ministry of Earth Sciences, Government of India. A Mann-Kendall trend test was undertaken using XLSTAT software and an Excel spreadsheet (https://www.xlstat.com/en/; last access on July 30, 2018). Further details of this analysis are provided in the Supplementary Information.

Finally, to understand the relationships between water-level changes, aquifer heterogeneity, and groundwater quality, we compiled groundwater electrical conductivity (EC) data from three different sources: (a) field measurements using a handheld EC meter, (b) CGWB reports (CGWB, 2015a, 2015b), and (c) the Isotope Fingerprinting of Waters of India (IWIN) report (IWIN, 2011; Deshpande and Gupta, 2012). The suitability of groundwater quality for irrigation is commonly evaluated from the salinity of groundwater as measured by EC. EC values less than 2000 μS/cm are categorized as fresh water and are considered safe and suitable for irrigation with respect to salt concentration. EC values ranging from 2000 to 4000 μS/cm are categorized as brackish water, and EC values above 4000 μS/cm are classified as saline and are considered unsuitable for irrigation (Kulkarni et al., 1989). Data from a total of 395 wells were used to prepare spatial plots of EC across the study area. Apart from compiling data from CGWB reports and the IWIN project, we also collected 200 samples from tube wells, hand pumps, CGWB piezometer locations, public tube wells, and state groundwater observation wells from depths of less than ~ 150 m bgl for analysing the salinity of groundwater in the study area. The wells were purged for more than 45 min before EC measurements were made.

4. Results

4.1. Spatio-temporal patterns of groundwater depletion

Fig. 2 shows the spatial distribution in groundwater levels (in terms of depth, bgl) at 5-year intervals from 1974 to 1999 and at annual intervals between 2001 and 2010. Groundwater level changes have not been uniform across the study area but were instead highly localized and structured. There is substantial spatial and temporal heterogeneity in groundwater levels, with declining, rising and relatively stable groundwater level trends observed in specific parts of the study area and varying over a lateral length scale of tens of kilometers.

Our compilation shows that groundwater levels over much of northwestern India were relatively shallow (~2 m bgl) during the 1970 s, apart from several local pockets in the western and southwestern part of the study area where groundwater levels of ~ 30 m bgl were recorded (Fig. 2). Between 1974 and 1987, the area of deep groundwater levels expanded into southwestern Punjab and western Haryana (see Fig. 1b for state boundaries and geographic locations). In the late 1980s and early 1990s, several pockets of groundwater level lowering began to emerge in the north-central and northeastern parts of the study area. Between 2000 and 2010, three distinct zones of rapid water-level lowering progressively emerged in our data. One zone is located along the incised valley of the Yamuna River, on the eastern edge of the study area, while another is centered along the Ghaggar-Hakra paleochannel, starting in the interfan area and extending along a curving trend toward the southwest (see Fig. 1c-d and 2). These zones expanded visibly year-on-year and have arcuate shapes that parallel the modern drainage system, with lateral dimensions of several tens of kilometers. The largest zone of depletion, however, is a more distributed area that extends over much of the proximal part of the Sutlej and Yamuna fans (Fig. 1d and 2). In contrast, the northwestern, southwestern and southern parts of the study area showed steady and consistently shallow groundwater levels throughout the study period.

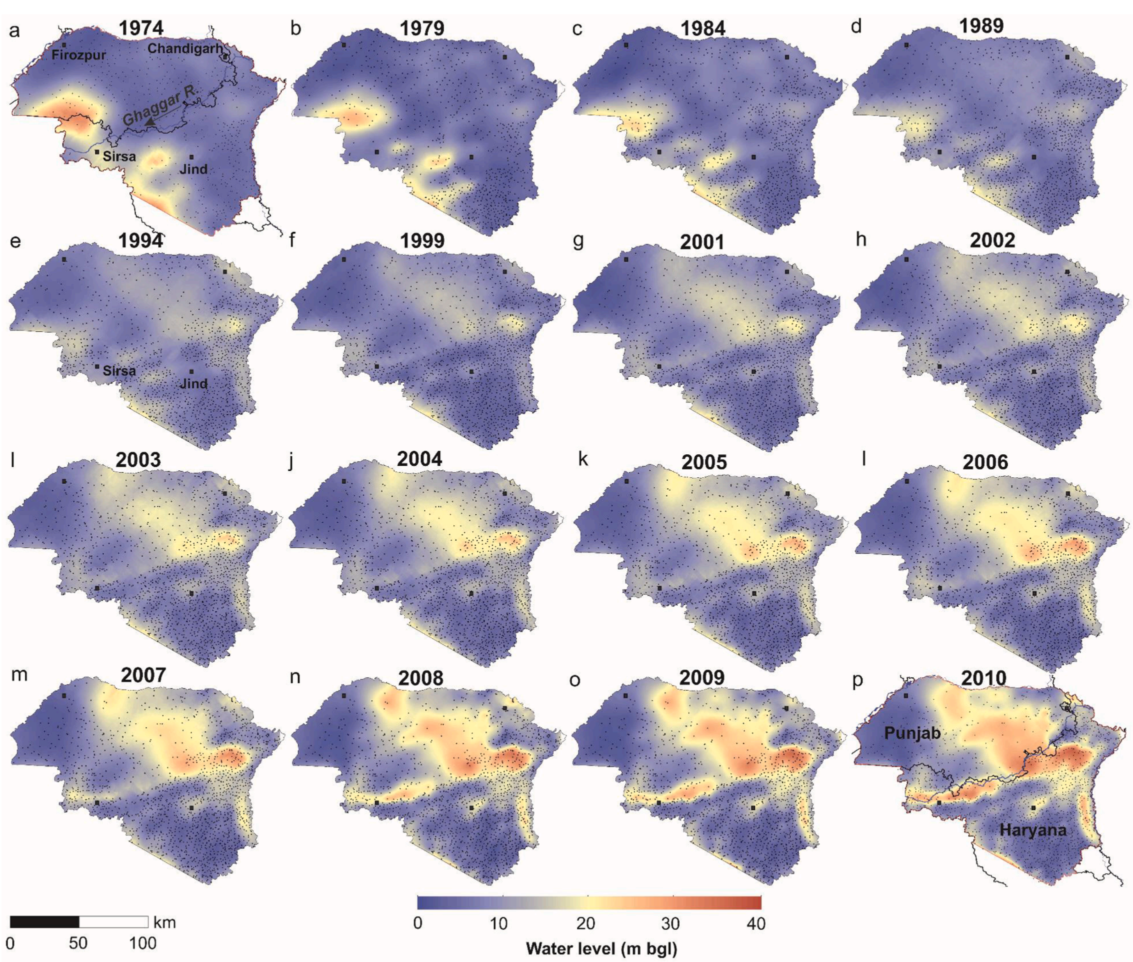

Fig. 2. Interpolated pre-monsoon groundwater levels over the entire study area, at 5-yearly intervals from 1974 to 1999, and at yearly intervals from 2001 to 2010. Black dots in each map show the locations of well records that were used in each interpolation; note that the number and spatial distribution of wells varies considerably between intervals. Blue lines show major rivers and black lines show state borders. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The net change in pre-monsoon groundwater levels between 1974 and 2010 (Fig. 3) shows distinct, localized zones of net groundwater level rise and fall. A large swathe of the northern part of the study area, encompassing much of central Punjab and northern Haryana, is characterized by marked declines in groundwater level. By 2010, about 40% (~26,000 km^2) of the study area had suffered groundwater level declines and water levels varied between ~ 20 and ~ 37 m bgl (Fig. 2p). In contrast, extensive areas of the southwestern part of the study area, in both Punjab and Haryana, experienced a rise of up to ~ 30 m in water levels.

4.2. Temporal variation in groundwater levels

Trend analysis of pre-monsoon water table depths indicates marked temporal variation across the study area (Fig. 4). The 73 wells with continuous records from 1974 to 2010 have distinct differences in groundwater level trends, with individual wells showing rising, steady, and declining trends (Fig. 4a). Evidence of inflection in behavior is apparent around 1999 when some but not all wells show the onset of a declining trend in groundwater level.

For the period 1974–2001, approximately 48% of the continuous well records (n = 47) show an increasing trend in groundwater level (Fig. 4b), at rates that vary from + 0.01 to + 1.12 m/yr with an average of + 0.37 ± 0.30 m/yr (±1 SD). A declining trend characterizes about 49% of the well records (n = 48) at rates of −0.01 to −0.28 m/yr, with an average of −0.09 ± 0.07 m/yr. Only three wells for which we have continuous records over this period show relatively stable groundwater levels.

For the period 2002–2010, the 1421 continuous well records show wide variability in groundwater level trends (Fig. 4c). Approximately 30% of wells (n = 420) show a rising trend in groundwater level at rates of + 0.01 to + 1.28 m/yr, with an average of + 0.15 ± 0.13 m/yr. By contrast, 69% of the wells (n = 983) record lowering of groundwater levels during this interval at rates of −0.01 to −2.41 m/yr, with an average of −0.49 ± 0.43 m/yr.

To understand the spatial variability of these differing groundwater level trends and elucidate the potential controls on water level variation, we plot the spatial distribution of the rate of change of rising and declining pre-monsoon groundwater levels for individual wells, superimposed on a map of the net change in groundwater level between 1974 and 2010 (Fig. 5a,b). These data indicate marked spatial variability in the distribution of wells with distinct rates of change across the different geomorphic units visible in Fig. 1d. Not surprisingly, declining groundwater level trends dominate the zones of marked groundwater depletion across the proximal and medial parts of the Sutlej and Yamuna fans (see Fig. 5 in conjunction with Fig. 1d). Similar declining trends are observed along the linear zones of depletion defined by the channel belt within the Yamuna River incised valley and the Ghaggar-Hakra paleochannel. By contrast, rising groundwater level trends are observed across much of southwestern Punjab and south and southwestern parts of Haryana, which correspond to the distal parts of the Sutlej and Yamuna fans. Rising groundwater level trends are also prominent in the interfan zone between the proximal Sutlej and Yamuna fans, which is another key zone that lacks evidence of marked depletion of groundwater.

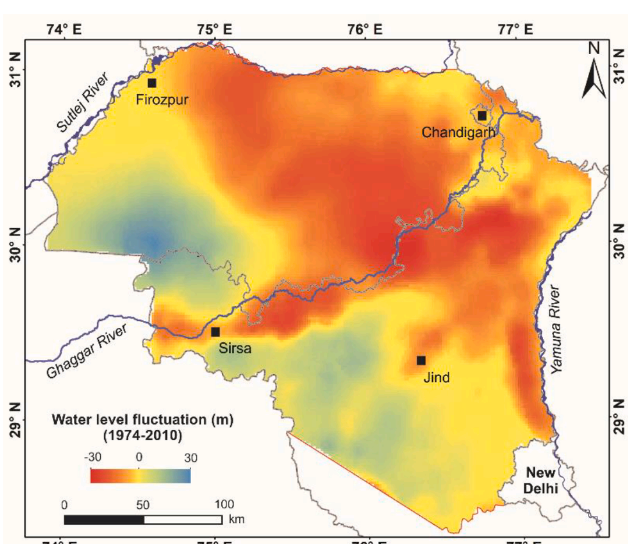

Fig. 3. Net pre-monsoon groundwater level fluctuation between 1974 and 2010 across the study area. Blue lines show major rivers, thick dark grey lines represent the state boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3. Cluster analysis of groundwater level trends

Groundwater level fluctuations can be caused by a number of internal or external controls. To understand the link between the patterns of groundwater level change illustrated above, internal aquifer characteristics, and external stresses, we first need to group wells that show similar groundwater level changes over time, so that we can assess the underlying drivers. The cluster analysis allowed us to identify regions with similar behavior and to distinguish the roles of different potential controls on groundwater level trends.

For the 98 continuous well records that span the period 1974–2001, the dendrogram in Fig. 6a shows six major clusters, each comprising a set of observation wells with similar trends in groundwater level through time (shown in different colors in Fig. 6b). We have cut the dendrogram at the 3rd order division at which we observe the level with the greatest distinction between clusters. Clusters 1 (n = 37 wells) and 2 (n = 34) are characterized by either no change or a gradual decline in groundwater levels over the period (Fig. 6c,d), and these are located in the proximal and medial areas of the Sutlej and Yamuna fans. By contrast, clusters 3 to 6 are characterized by rising groundwater level trends which display a variety of profile shapes (Fig. 6e–h) and are located exclusively in the distal parts of the Sutlej and Yamuna fans.

The 1421 continuous well records that span the period 2002–2010 fall into four major clusters (Fig. 7). Cluster 1 (n = 24) is characterized by groundwater levels that start low and decline throughout the period. Similarly, cluster 2 (n = 106) also shows a declining trend, albeit from higher starting levels. Cluster 3 (n = 353) is characterized by higher initial groundwater levels and a slow decline rate. Cluster 4, the largest cluster of observation wells (n = 938), is characterized by shallow but steady groundwater levels over the period. The clustering technique enables us to segment the study region into zones characterized by similar groundwater level trend profiles between 2002 and 2010 (Fig. 7b). Wells in clusters 1 and 2 are located across the proximal Sutlej fan, at the edges of the fans and the interfan area, and along the trace of the Ghaggar-Hakra paleochannel and Yamuna River channel belt. Wells in cluster 3 are distributed on the proximal parts of the Yamuna and Sutlej fans. Cluster 4, with steady and shallow groundwater levels, dominates the distal Sutlej and Yamuna fans in the western and southern parts of the study area (Fig. 7b).

4.4. Estimation of groundwater storage changes

The spatial heterogeneity in groundwater level changes over the study area between 1974 and 2010 leads to similar heterogeneity in storage changes (Fig. 8 & S4). Summing the cell-wise storage changes, we find that over the entire period from 1974 to 2010, the total loss in groundwater storage for the ~ 66,000 km^2 study area is −36.01 ± 0.37 km^3 for the pre-monsoon period, and –32.03 ± 0.37 km^3 for the post-monsoon period. These volumetric rates correspond to spatially- and temporally-averaged lowering rates of −1.47 ± 0.02 cm/yr and −1.31

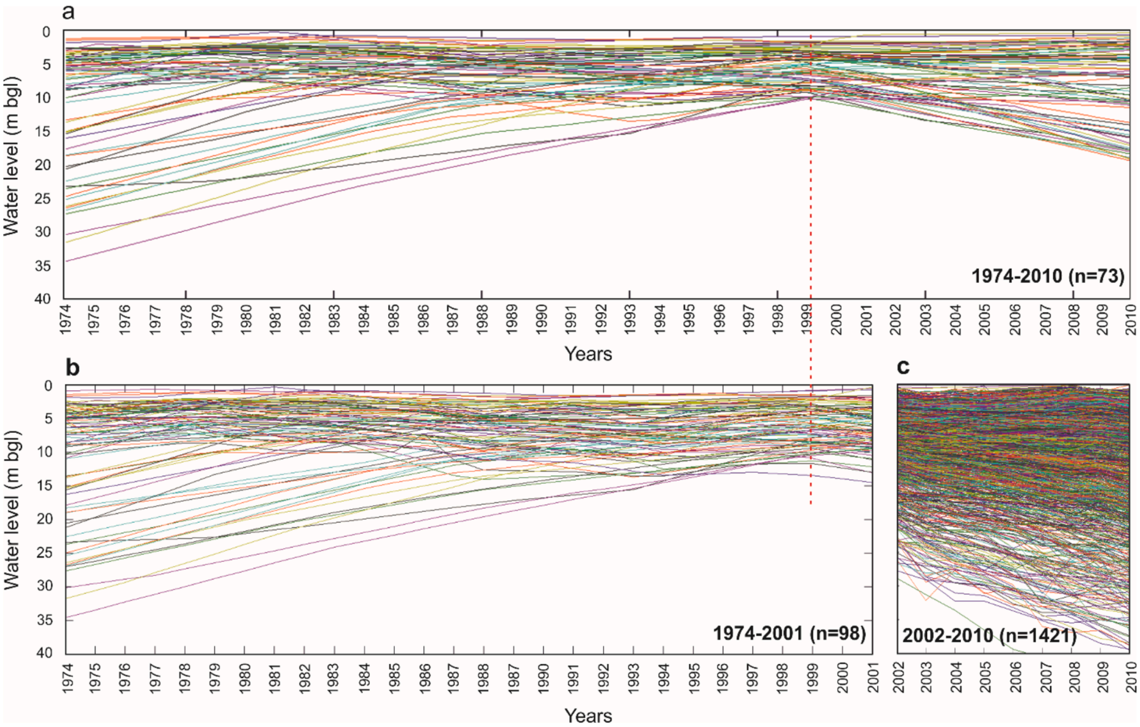

Fig. 4. Long-term groundwater level trends for wells that are continuous over different parts of the study period. (a) 1974 to 2010 – note the inflection in behavior in 1999 between rising and declining trends for some, but not all, wells, (b) 1974 to 2001 – dominantly rising. Line colors indicate individual wells and are arbitrarily assigned.

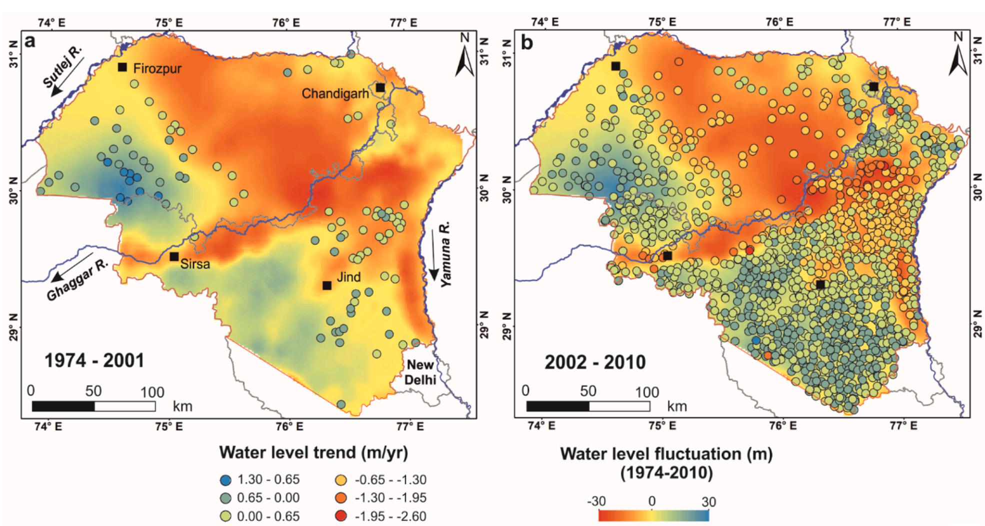

Fig. 5. Spatial distribution of trends in pre-monsoon groundwater level, overlain on interpolated net pre-monsoon water level fluctuation between 1974 and 2010, across the study area between: (a) 1974 and 2001 ($n = 98$ observation wells), and (b) 2002 and 2010 ($n = 1421$ observation wells). Colored circular symbols indicate the relative values of the rising or declining gradient of groundwater level change (m/yr); positive values indicate rising trends and negative values indicate declining trends in water level.

$\pm$ 0.02 cm/yr, respectively, for the pre- and post-monsoon periods. Note, however, that this averaging obscures both important temporal variability (e.g., Fig. 4) and spatial variability (Fig. 8a & S3a) in storage change. To better understand the spatio-temporal distribution of groundwater storage changes in view of the trend analysis discussed above, we therefore define separate pre- and post-monsoon estimates of groundwater storage change for 1974–2001 and 2002–2010.

For the period 1974–2001, we estimate a total gain in groundwater storage of about + 0.58 $\pm$ 0.35 km^3 for the pre-monsoon period and + 0.40 $\pm$ 0.35 km^3 for the post-monsoon period (Fig. 8b & S4b). There is marked spatial variability in groundwater storage change across the study area, ranging from an increase in the distal Sutlej and Yamuna fans to a decrease in the proximal and medial fan areas. From 2002 to 2010, a decrease in groundwater storage is observed over nearly all of the study area, with a total loss of storage of –32.30 $\pm$ 0.34 km^3 during the pre-monsoon period and $-$24.42 $\pm$ 0.34 km^3 during the post-monsoon period. This corresponds to an average rate of storage decline of $-$6.12 $\pm$ 0.06 cm/yr for the pre-monsoon period and $-$4.63 $\pm$ 0.06 cm/yr for the post-monsoon period (Fig. 8c & S4c). Not surprisingly, the greatest declines in storage are found across the proximal and medial parts of the Sutlej and Yamuna fans, along the Ghaggar-Hakra paleochannel, and along the incised valley of the Yamuna River.

4.5. Rainfall variability and trend analysis

To understand the extent to which the observed pattern of

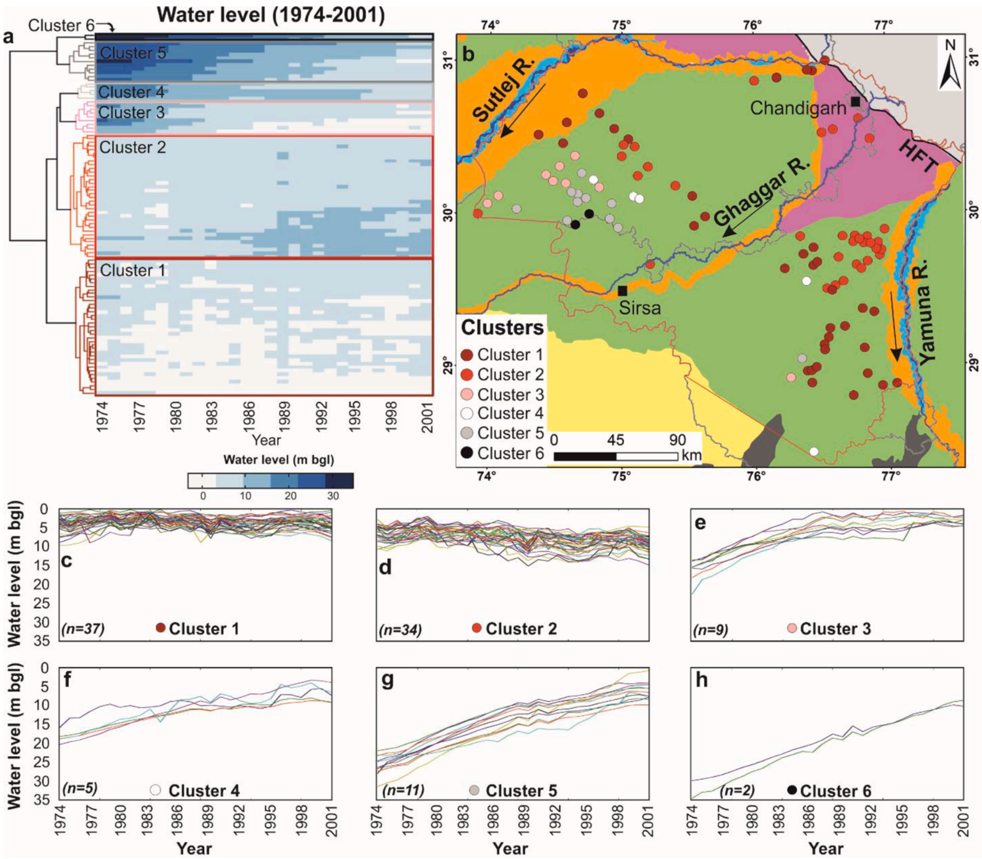

Fig. 6. Results of the hierarchical cluster analysis for the 98 continuous well records that span 1974 to 2001. (a) Dendrogram and 'heat' map of well records for pre-monsoon groundwater levels. Heat map shading indicates water level in m bgl, from very deep (dark blue) to very shallow (white). Six major clusters are present; these are delineated by the colored boxes. (b) Spatial distribution of wells belonging to each of the water level time-series clusters, overlain on the geomorphic map of the study area (see Fig. 1d for geomorphic units). Colored circular symbols indicate the different time-series clusters of the water level records. (c)–(h) Time-series of water levels for wells in each of the six major clusters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

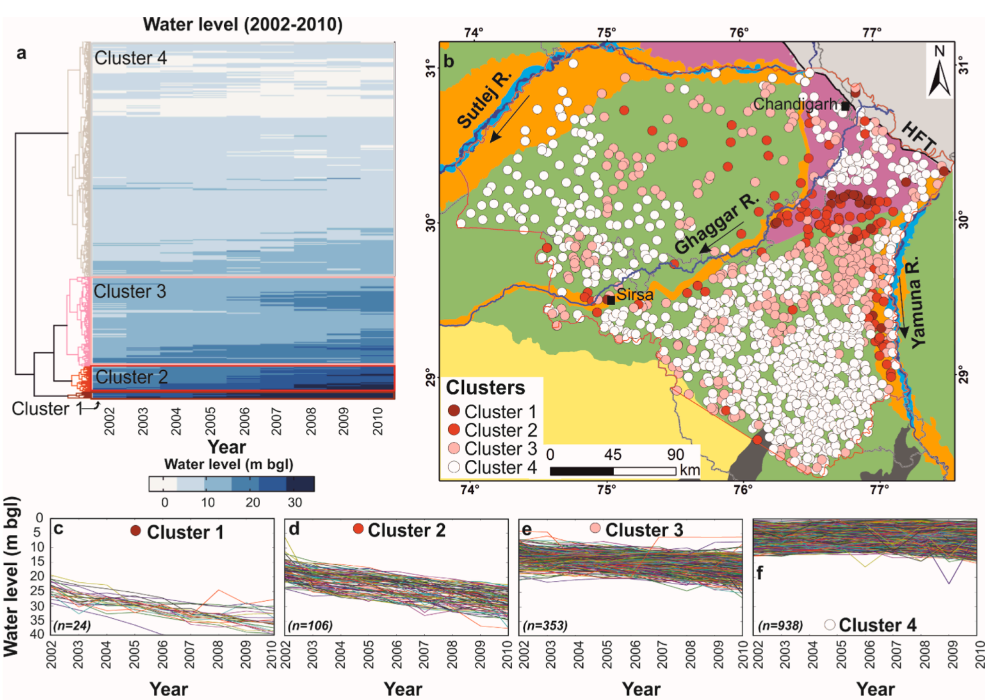

Fig. 7. Results of the hierarchical cluster analysis for the 1421 continuous well records that span 2002 to 2010. (a) Dendrogram and 'heat' map of well records for pre-monsoon groundwater levels. Heat map shading indicates water level in m bgl, from very deep (dark blue) to very shallow (white). Four major clusters are present; these are delineated by the colored boxes. (b) Spatial distribution of wells belonging to the water level time-series clusters, overlain on geomorphic map of the study area (see Fig. 1d for geomorphic units). Colored circular symbols indicate the different time-series clusters of the water level records. (c)–(f) Time-series of water levels for wells in each of the four major clusters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

groundwater level changes can be ascribed to local rainfall variability, we compared our water-level results to rainfall records from 1974 to 2010. The mean annual rainfall in the study region for 1974–2010 was 523 mm with a standard deviation of ~ 121 mm. The minimum and maximum annual totals were 270 mm during 1987 and 759 mm during 1976, respectively. A total of 84% of the annual rainfall occurs during the monsoon season (Table S1). However, both total annual and annual monsoon rainfall show substantial decreases in mean values estimated over the 1974–2001 and 2002–2010 intervals (Tables S2 and S3). In contrast, total non-monsoon rainfall has shown only a slight change

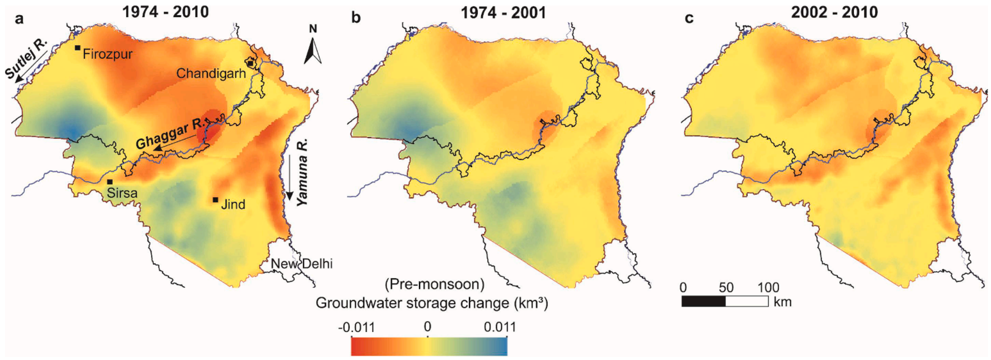

Fig. 8. Estimates of groundwater storage change (in km^3) derived by interpolation from *in situ* measurements of groundwater levels for pre-monsoon periods: (a) 1974 to 2010, (b) 1974 to 2001, and (c) 2002 to 2010. Equivalent post-monsoon storage changes are shown in the Supplementary Information, Fig. S3.

through time, with mean values of 78 mm for 1974–2001 and 91 mm for 2002–2010.

We used least-squares regression to fit linear trends to the spatially averaged data on total annual rainfall, total monsoon rainfall, and total non-monsoon rainfall over the period 1974–2010. We subtracted the best-fit linear trend from the time series to examine the residuals (Fig. 9). The results show a weak declining trend in both total annual and total monsoon rainfall over the study period, albeit with low correlation coefficients. In contrast, non-monsoon rainfall shows no apparent trend (Fig. 9). The results of the Mann-Kendall trend test are reported in Table S2. We find statistically significant decreases in July and August rainfall totals over the period 1974–2010, as well as significant increases in April, September, and October rainfall totals, both at the 5% level of significance (Fig. 10a). Other months show varying trends that are not significant at the 5% level. Significant decreasing trends are observed for total monsoon rainfall and total annual rainfall over this period, again at the 5% level of significance (Fig. 10b).

The Mann-Kendall test provided the trends of monthly, total annual, total monsoon, and total non-monsoon rainfall over the separate intervals 1974 to 2001 and 2002 to 2010. These results are reported in Tables S2 and S3. Between 1974 and 2001, we observe statistically significant decreasing trends for July and September monthly totals and total annual and total monsoon rainfall. For February, an increasing trend was observed at the 5% level of significance (Fig. 10b). In stark contrast, between 2002 and 2010, we observe statistically significant increasing trends for July, September and October monthly totals, total monsoon rainfall, and total annual rainfall, all at the 5% level of significance (Fig. 10c). Thus, the period 2002–2010, which contains the largest and most rapid falls in groundwater level within our whole study period, is largely characterized by stable or rising trends in monsoon and total annual rainfall.

4.6. *Groundwater quality*

Measurements of electrical conductivity, a proxy for groundwater salinity, show marked spatial variability across the study area from 198 to 22,800 µS/cm (Fig. 11). Most of northeastern Punjab and northern Haryana are characterized by low electrical conductivity with EC values of less than 2000 µS/cm. By contrast, southern Haryana and southwestern Punjab are characterized by zones of significantly higher EC values with EC ranging from 2000 to 4000 µS/cm. Locally, isolated pockets of high electrical conductivity with values greater than 4000 µS/cm are observed. The influence of these spatial variations in groundwater electrical conductivity, and hence salinity, on patterns of groundwater level change are examined below in the Discussion.

5. Discussion

Our results, derived from the compilation of a large dataset of *in situ* groundwater observation wells, indicate that groundwater in northwestern India has not undergone uniform depletion as might be inferred by regional-scale GRACE results (e.g., Rodell et al., 2009, 2018; Tiwari et al., 2009). Instead, groundwater level variations are characterised by marked and highly structured spatio-temporal heterogeneity. We identify several sub-regions, based on the geomorphic and stratigraphic framework of the alluvial aquifer system established by van Dijk et al. (2016a), that show distinct trends in groundwater levels, encompassing both falling, rising and static trends over the period 1974–2010. This spatial and temporal heterogeneity is not apparent in GRACE records because of the latter's low spatial resolution.

Asoka et al. (2017) compared groundwater storage changes and estimated recharge with rainfall and abstraction indices across India. For northwestern India, they demonstrated convincingly that abstraction was slightly more important than rainfall in controlling

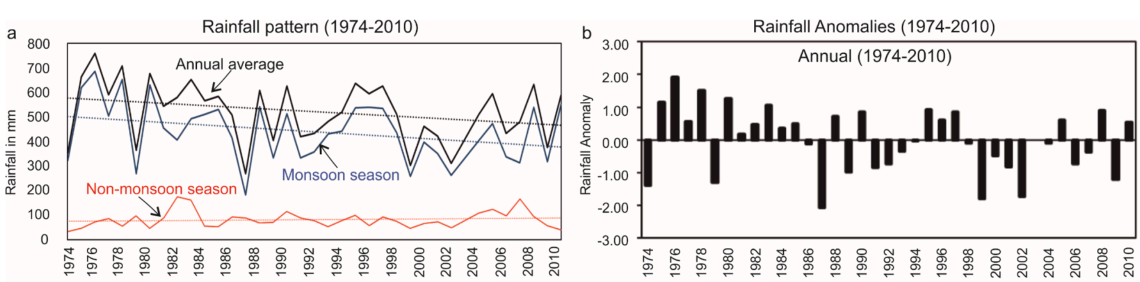

Fig. 9. Rainfall pattern of the study area between 1974 and 2010, a) Annual and seasonal (monsoon and non-monsoon) rainfall trend, the continuous black line is annual average rainfall, the continuous blue line is for monsoon season, and continuous red line for the non-monsoon season during the study period. Dotted black, blue and red continuous lines indicate trends in the study area during the annual, monsoon and non-monsoon seasons, respectively. b) Rainfall anomaly of Sutlej-Yamuna plain in northwest India between 1974 and 2010. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

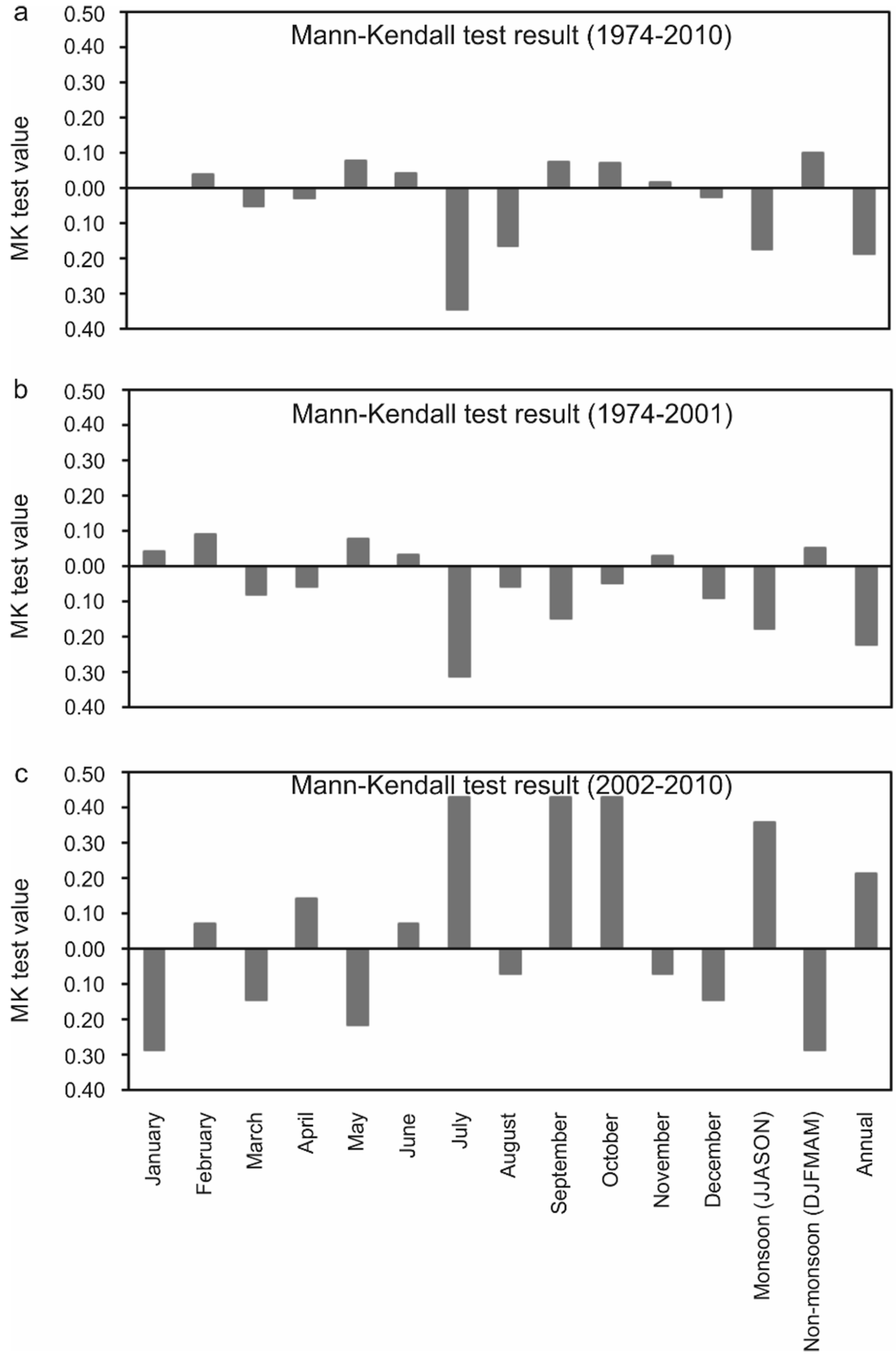

Fig. 10. Mann-Kendall trend test results of rainfall in the Sutlej-Yamuna plain in northwest India for the period of a) 1974 to 2010, b) 1974 to 2001, and c) 2002 to 2010.

groundwater storage changes, whereas rainfall was more dominant in determining recharge. Thus, they argued that rainfall provided both direct and indirect controls on water storage change. Asoka et al. (2018) refined this result by showing that low-intensity monsoon rainfall was especially important in determining recharge in the area. Our work complements and extends these earlier studies by documenting the detailed spatio-temporal pattern of groundwater level variation and consequent storage change. In this section, we first discuss relationships between storage change and available measures of groundwater abstraction before considering the impacts of spatial heterogeneity in the alluvial aquifer system, and of groundwater quality, on the pattern of storage change. We close with some implications for groundwater resource management that can be drawn from our results.

5.1. Link between groundwater abstraction and depletion

To understand how groundwater abstraction influences the spatio-temporal pattern of groundwater depletion, we compared district-level estimates of tube well density derived from the Minor Irrigation Census (MoWR, 2007) (Fig. 12a,b) and available district-averaged data on groundwater abstraction (Fig. 13a–c) with our patterns of ground-water level change derived from *in situ* well records.

Both tube well density and estimated annual volumes of ground-water abstraction are greatest in central and northern Punjab, in the

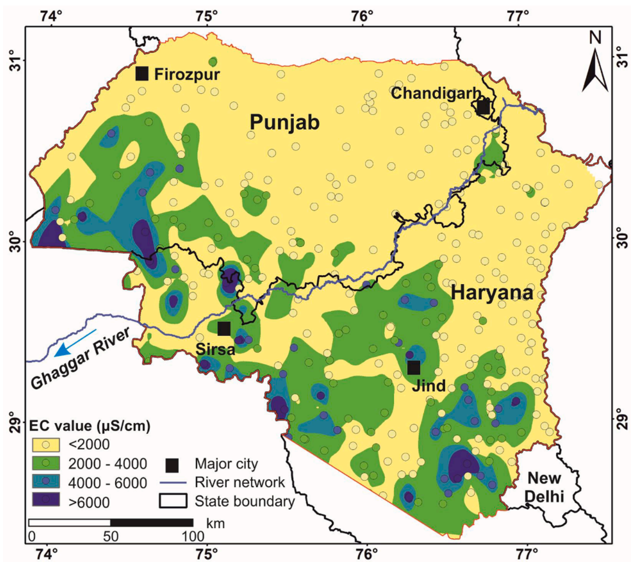

Fig. 11. Map of spatial variations in groundwater electrical conductivity (EC), compiled from UNDP (1985), CGWB (2014a & b], and our field measurements.

proximal and medial parts of the Sutlej fan (Fig. 1d, 12a, and 13a-c). Moderate to high tube well densities are also found across the proximal and medial parts of the Yamuna fan and along the incised valleys of the present-day Sutlej and Yamuna rivers, while the lowest values are found in the interfan area and in southwestern Punjab and southern Haryana, on the distal parts of the Sutlej and Yamuna fans (Fig. 12a,b). Volumes of groundwater abstraction show similar spatial patterns across the three years of available data, with high volumes of abstraction from aquifers underlying the proximal and medial parts of the Sutlej and Yamuna fans, and lower values from the distal fan areas (Fig. 13a–c).

These abstraction patterns are similar to abstraction patterns derived from the model-based assessment of Cheema et al. (2014). There is a first-order correspondence between at least some of the areas of high tube well density and high abstraction volume and the areas of marked groundwater depletion since 2000, especially across the proximal and medial Sutlej fan (e.g., compare Fig. 12a-b and 13a-c with Fig. 12c). This trend matches extremely well with the remarkable shift from conventional low-horsepower surface pumps to more powerful submersible pumps capable of extracting water from deeper levels in this region during 2001–2005 (Kaur and Vatta, 2015). That shift may have been an adaptation to falling groundwater levels, but it certainly facilitated exploitation from deeper wells. Similarly, low tube well densities and low abstraction volumes in the distal parts of the Sutlej and Yamuna fans appear to correlate with areas characterized by rising groundwater level trends.

To support this finding further, we have compiled the available data on the production of major crops (wheat and rice) and the area covered by these crops from 1960 to 61 to 2017–18 for Punjab and Haryana states (Fig. 14) from Statistical Abstract of Punjab and Haryana (GoH, 2008, 2020; GoP, 2016, 2019). The area under rice and wheat cultivation increased rapidly from 1960 to 61 to 2000–01 but slowed markedly after 2000–01 for Punjab and Haryana. For example, the area of rice cultivation increased rapidly from 1920 to 10543 km^2 between 1966 and 67 and 2000–01, and then to 14220 km^2 in 2017–18 for Haryana (GoH, 2008 & 2020). For Punjab, rice cultivation area increased rapidly from 2270 to 26120 km^2 between 1960 and 61 and 2000–01, and then to 30640 km^2 in 2017–18 (GoP, 2016, 2019).

In detail, however, the groundwater level change pattern does not always match either tube well density or estimated abstraction volume. The Ghaggar-Hakra paleochannel and the fluvial channel belt in the Yamuna River incised valley have both experienced rapid groundwater level declines since 2000 (see Fig. 2) but are characterised by only moderate values of tube well density and abstraction. Likewise, the variability in groundwater level change across the Yamuna fan, with

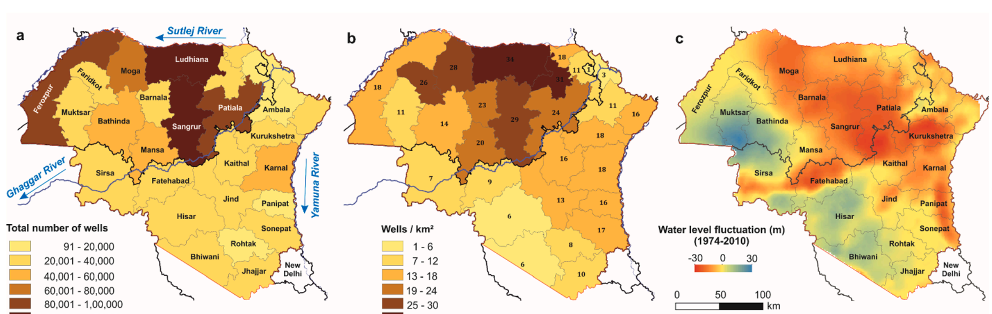

Fig. 12. (a) Total number of tube wells per district and (b) well density per square km in each district (MoWR, 2007). (c) District-wise net pre-monsoon groundwater level fluctuation between 1974 and 2010 across the study area. Blue lines show major rivers, thick grey lines represent the state boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

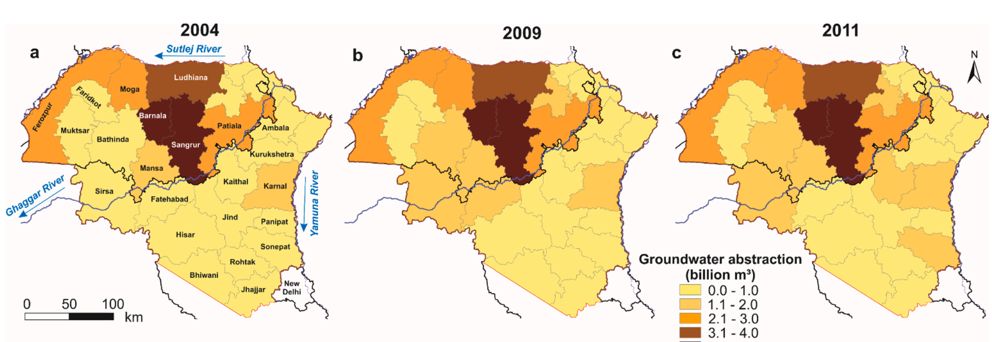

Fig. 13. Spatial variation of groundwater abstraction (in billion m^3) for: (a) 2004, (b) 2009, and (c) 2011 (CGWB, 2006, 2012, 2014a & b).

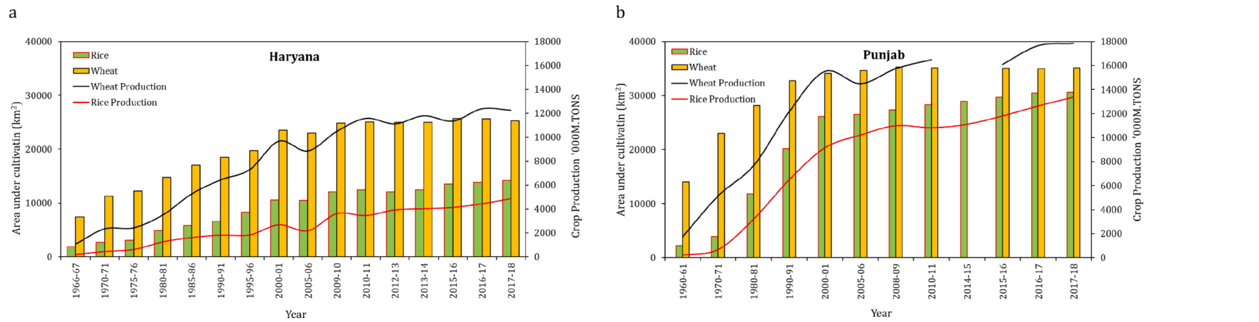

Fig. 14. Historical trend in wheat and rice crop area and production, (a) between 1966 and 2017–18 for Haryana state, and (b) between 1960 and 2017–18 for Punjab state in northwest India. (Source: statistical abstract of Haryana and Punjab 2006–07 to 2018–19).

groundwater decline in the proximal and medial parts of the fan and groundwater level rise in the distal sectors, does not match the relative uniformity of tube wells density and abstraction volumes across the fan. From this partial match, we infer that spatial variation in abstraction is an important element in the evolution of groundwater levels across the study area, but that it cannot solely explain the spatial variability that we see. This disparity may, of course, arise because records of tube well numbers and estimates of abstraction are not sufficiently accurate. More accurate and granular estimates of both tubewell numbers and abstraction volumes over longer time intervals would enable better comparison of the potential link between these variables.

5.2. Effect of aquifer stratigraphy on patterns of groundwater depletion

The sediments of the Indo-Gangetic foreland basin form one of the most important alluvial aquifers in the world, yet the role of aquifer stratigraphy in characterising the groundwater system is not well understood. Bonsor et al. (2017) conceptualized a set of aquifer typologies for the basin alluvium to characterize aquifer properties at a transboundary scale, although this was only linked at a broad scale to the basin sedimentary architecture. van Dijk et al. (2016a) explored this linkage in more detail using aquifer thickness logs from the CGWB across the study area and showed in detail how the geomorphology of surface sediment routing systems could be used as a proxy to gain insight into subsurface sedimentary architecture, and thus heterogeneity of the alluvial aquifer system. Importantly, they also showed that the distribution of aquifer bodies and the proportion of aquifer material in the subsurface both depend at a broad scale on the depositional mosaic of the alluvial sedimentary systems which deposited the aquifer sediments. Because the groundwater level response to abstraction in a heterogeneous aquifer system should be strongly determined by the aquifer characteristics, it is instructive to compare the pattern of groundwater level change with the geomorphic and stratigraphic framework proposed by van Dijk et al. (2016a).

Fig. 15 plots the percentage of aquifer material determined from boreholes superimposed on maps of groundwater level for 2010 across the study area. As with tube well density and abstraction volume, there is some correspondence between the geomorphic and stratigraphic framework of van Dijk et al. (2016a) and at least some of the patterns of groundwater level change (Fig. 15). Four points can be taken from this correspondence.

First, we observe rapid groundwater level decline after 2000 in several areas that are characterized by abundant aquifer material and thick aquifer bodies in the subsurface, particularly the proximal and medial Sutlej and Yamuna fans and the incised valleys of the Sutlej and Yamuna rivers. These areas also show high values of our abstraction metrics (see Fig. 13 in conjunction with Fig. 1d), and it is difficult from these results to determine the relative importance of abstraction or aquifer characteristics in driving the groundwater response. It seems plausible, nevertheless, that groundwater exploration knowledge gained

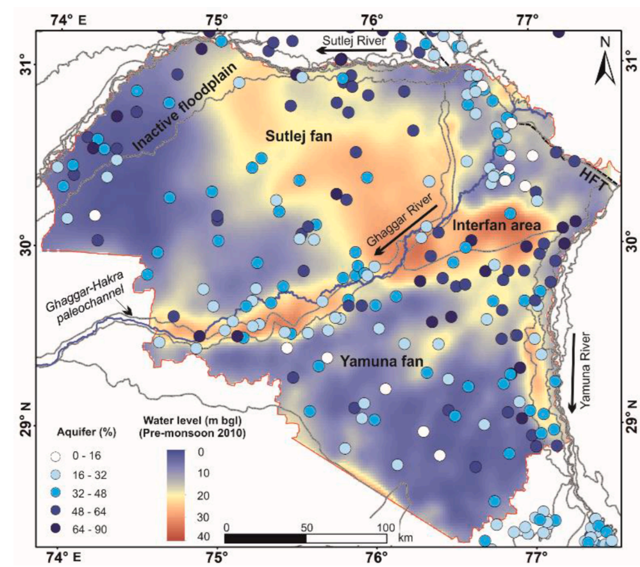

Fig. 15. Major geomorphic units and percentage of aquifer material in the uppermost 200 m of the subsurface (modified from van Dijk et al., 2016a), overlain on interpolated pre-monsoon 2010 groundwater levels. Colored circular symbols represent increasing percentage of aquifer material, as determined from CGWB aquifer-thickness logs. See van Dijk et al. (2016a) for details.

from institutional studies and drillers' experience for decades has led to an increase in tube well drilling, including the adoption of new technologies (Kaur and Vatta, 2015), and groundwater abstraction in these areas with abundant aquifer material. In recent years, areas with abundant aquifer material may have been overexploited beyond the seasonal resilience of the system.

Second, spatial variability in the abundance of aquifer bodies within the Yamuna fan system also matches the pattern of groundwater level change, with areas characterized by declining groundwater levels corresponding to areas with greater abundance of aquifer bodies, and stable or rising levels corresponding to areas with fewer aquifer bodies (Fig. 15). Despite significant changes in the abstraction metrics, abstraction has increased in areas along the Yamuna River (Fig. 13a–c), and this has significant implications for the baseflow reduction in the Yamuna as documented for the Ganga River by Mukherjee et al. (2018).

Third, the downstream sections of the Ghaggar-Hakra paleochannel in southern Haryana and Punjab also show evidence for marked declines in groundwater levels after 2000 despite only moderate estimates of abstraction. The Ghaggar-Hakra paleochannel is characterized by thick and abundant aquifer bodies, especially in the shallow subsurface (van Dijk et al., 2016a; Singh et al., 2017). It is possible that the occurrence of abundant aquifer material along the paleochannel was a factor in the initial onset and subsequent growth of tube well-based irrigation in this arid region. Pumping from these tube wells will also affect wells that lie outside the paleochannel, in areas where aquifer material is less abundant. For example, pumping from a battery of about 100 tube wells along a relatively small stretch of the Yamuna River in Delhi, in an alluvial aquifer system that is likely similar to the one in our study area (MacDonald et al., 2016) led to groundwater drawdown over a 250 km^2 area of influence (Soni et al., 2018]. Thus, pumping in the distal part of the paleochannel from a regionally narrow set of aquifer bodies may lead to greater depletion in adjacent areas that lack such abundant and thick aquifer bodies. Furthermore, Singh et al. (2017) demonstrated that the Ghaggar-Hakra paleochannel is an underfilled incised valley that forms a depression at the surface. Here, sandy loam soils developed in very fine-grained alluvial sediments, and show soil conditions that are highly favourable for agriculture due to their high fertility compared to outside of the incised valley (Courty, 1995). It is possible that this flat-floored depression was one of the first parts of the region to be intensively farmed owing to the presence of fertile soils, and thus one of the first to be irrigated through groundwater exploitation. Thus, the marked depletion along the paleochannel may partly be a consequence of a 'first occupation' effect.

Finally, the proximal interfan region between the apices of the Sutlej and Yamuna fans is characterized by relatively low percentages of aquifer body material in the upper ~ 200 m (Fig. 15), corresponding to a low specific yield of c. 5% (Fig. S2) (UNDP, 1985; CGWB, 2009; 2012). Groundwater level changes in this area are highly variable (see Fig. 3) despite moderate values of abstraction, which may be a direct result of the limited and highly heterogeneous distribution of aquifer material in the subsurface (van Dijk et al., 2016a; Singh et al., 2017).

Interestingly, the area of the Sutlej River incised valley shows high aquifer percentage values but has undergone little if any decline in water levels (Fig. 15), despite high tube well densities and abstraction volumes. This may indicate that the aquifer bodies in this sector have high lateral and vertical connectivity with the Sutlej River and are replenished regularly either by vertical or lateral recharge during the monsoon season, allowing the area to sustain high abstraction without significant decline in groundwater levels. As a potential analogy, extraction of 0.055 to 0.062 billion cubic metres per year from a 12 km^2 area of the alluvial aquifer underlying the present Yamuna River flood plain near Delhi over the last 15 years has not led to significant lowering in groundwater level (Shekhar and Prasad, 2009; Kumar et al., 2017; Soni et al., 2018). Overall, we infer that both spatial patterns of abstraction and spatial heterogeneity in the alluvial aquifer system play important roles in setting regional-scale groundwater level change. Further exploration of the relative roles and interactions of these factors requires regional-scale modelling efforts, such as those of Shekhar et al. (2020), that are beyond the scope of this study.

5.3. Linkage between groundwater storage changes and rainfall

Rainfall is the main source of groundwater recharge in northwest India, as clearly evidenced from the isotopic composition of groundwater and rainfall (Joshi et al., 2018, 2020; Semwal et al., 2020). Here, we explore the relationship between temporal variability in rainfall patterns and groundwater storage changes. We estimated rainfall and groundwater storage anomalies to identify the linkage between groundwater storage change and rainfall. The rainfall and groundwater storage anomalies has been assessed on annual and seasonal scale. The annual and seasonal rainfall anomalies show marked variability during the period 1974–2010 (Fig. 16) although these changes are not exactly mirrored in groundwater storage anomalies at annual or seasonal scales. In contrast to year-by-year variation in rainfall, annual groundwater storage consistently shows positive values until 2000 and more negative values after 2000. After 2000, groundwater storage continued to fall despite high rainfall in some years (Fig. 16).

Furthermore, it is also important to understand the impact of the long-term trends in rainfall on crop productivity and groundwater demand. For example, the declining trend observed for September (Fig. 10b) has a determinant effect on crop productivity during the monsoon season, whereas the statistically significant increasing trend observed for February has a negative impact on crop harvesting during

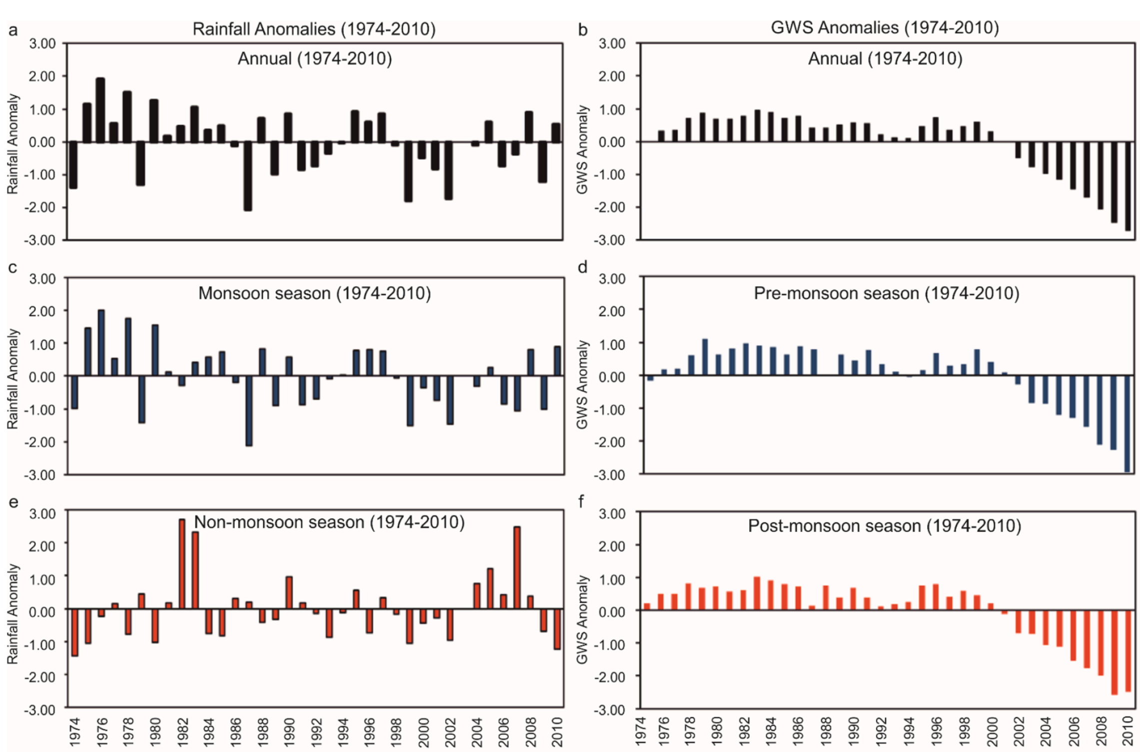

Fig. 16. Rainfall anomalies of the study area for the period of 2002 to 2010, a) Annual rainfall anomaly, c) monsoon season, and e) non-monsoon season rainfall anomaly. Groundwater storage anomaly for the period of 2002 to 2010, b) Annual, d) pre-monsoon, and f) post-monsoon season for northwest India.

the non-monsoon season (Ambast et al., 2006). Consistent drought years, such as those observed during 1999–2002, are likely to have resulted in over-exploitation of groundwater to such an extent that abstraction far exceeded the recharge, and therefore a consistent decline in groundwater level after 2000. Even though there were intermittent years of positive rainfall anomalies (e.g., 2005, 2008, 2010), these do not appear to have been sufficient to reverse the negative trend in groundwater storage. Recent modeling efforts by van Dijk et al. (2020) noted only a weak relationship between rainfall and observations of groundwater level changes. They further showed that the response of groundwater levels in the study area to variation in rainfall is fairly rapid in areas experiencing groundwater level rise but is delayed by a few months in areas of groundwater level fall.

5.4. Linkage between water quality and heterogeneity in groundwater level change

MacDonald et al. (2016) highlighted the importance of groundwater quality, in particular salinity, in constraining groundwater sustainability in the Indo-Gangetic basin. Here, we explore how groundwater quality may affect patterns of groundwater level variation in our study area. One of the most striking aspects of our analysis of spatial and temporal patterns in groundwater depletion is the marked absence of groundwater depletion in a large area of southwestern Punjab and southern Haryana. These areas are characterised by relatively high water tables that show either stable or rising trends (Fig. 5). The absence of marked depletion in these areas cannot be purely explained by reduced abstraction because of poor-quality aquifers in these areas, because while aquifer body percentages are generally lower than in northern Punjab and Haryana (where marked depletion is observed), there are still extensive aquifer bodies present in the subsurface (van Dijk et al. 2016a).

Comparison of the spatial distribution of EC values (see Fig. 11) with the spatial pattern of groundwater levels for 2010 (see Fig. 2p) indicates that water quality is likely to be another factor in groundwater level heterogeneity in the region. Areas of low-EC freshwater across the proximal and medial Sutlej and Yamuna fans correspond to areas of rapid groundwater depletion, although low EC values are also found in the less-exploited interfan area. Distal parts of both fans, however, show a marked correlation between high EC values and high, rising or stable groundwater levels. The presence of brackish to saline groundwater as a limiting factor for irrigation use has been indicated by several local studies (Kamra et al., 2002; Kumar et al., 2014; Chopra and Krishan, 2014; Lapworth et al., 2017; Sharma et al., 2017; Gupta and Misra, 2018), but this correlation has not previously been demonstrated at the scale of our study. For example, Kumar et al. (2014) showed that groundwater in southwestern Punjab is largely marginally suitable to unsuitable for irrigation purposes because of its high salinity. Similarly, Chopra and Krishan (2014) showed that the groundwater is marginally fit to unfit for irrigation purposes in many districts in southwestern Punjab. These observations provide the likely explanation for the absence of marked groundwater depletion in these areas. The origin of the saline groundwater is poorly understood but is likely because of both high evaporation rates in this semi-arid region and irrigation return flow (Uppal, 1972; Kulkarni et al., 1989; Ritzema et al., 2008; Joshi et al., 2018, 2020; Semwal et al., 2020). These areas are served by extensive canal networks, and water from these is being utilized for irrigation (Buck, 1906; UNDP, 1985; Singh, 2010, 2011; Singh and Bhangoo, 2013), carries high concentration of salts, and contributes to local recharge (CGWB, 2011b, 2014b). Additional support for this relationship comes from modelling by van Dijk et al. (2020), which showed that observed groundwater levels in these distal parts of the study area cannot be adequately simulated by considering rainfall and abstraction alone; instead, an additional component, inferred to be due largely to canal recharge and irrigation return flow, is required.

5.5. Implications for groundwater management and policy

The patterns of groundwater level lowering over time that we map from *in situ* data offer guidance on where mitigation efforts to tackle rapid groundwater depletion in the region are most needed, and could be most effective. We identify several areas of high rates of depletion that require immediate action in terms of enhanced monitoring of groundwater level change and intervention to mitigate against pressure from abstraction. These areas are north-central Punjab and Haryana (particularly Sangrur, Patiala, Kaithal, Kurukshetra and Moga districts), and areas along the Ghaggar-Hakra paleochannel (the northern part of Fatehabad, Sirsa, and the southern part of Mansa districts) (Singh et al., 2017) and the Yamuna incised valley (the eastern part of Panipat and Sonepat districts). Regional-scale modeling work in this region has already demonstrated that the situation is likely to become worse within the next decade or so, and declines ranging from 5 to 10 m to as much as 28 m can be expected in several districts in Punjab and Haryana (Shekhar et al., 2020). Our work has identified fine-scale groundwater depletion patterns in northwestern India, and provides a framework for decision making with respect to developing management strategies to counteract the significant decline in groundwater storage in this region. The situation is critical in this region because of the consequences of overexploitation for future food production (Zaveri et al., 2016).

The groundwater depletion issue in northwest India has prompted both state and central government departments to launch a series of both reactive and proactive water-saving programmes at local and regional scales. Sustainability of groundwater resources can be achieved by either increasing the supply of surface water or reducing demand for groundwater (Scanlon et al., 2012a). The former is not readily plausible, so it is the demand side that needs to be addressed through increased irrigation efficiency (Fishman et al., 2015), diversification to less water-hungry crop types (Davis et al., 2018), or altered farm economics through energy pricing (Barik et al., 2017). One of the key policy initiatives that was triggered by the groundwater crisis was the 2009 "Sub-Soil Water Act" instituted by the governments of Punjab and Haryana (Singh, 2009). This act imposed restrictions on the timing of planting rice in the pre-monsoon period so that farmers were not using groundwater to irrigate fields in the hottest part of the year, with consequent significant loss of water to evaporation. Our data cannot address whether this policy has been successful because the analysis does not extend beyond 2010; however, Tripathi et al. (2016) reported a decrease in the rate of groundwater level decline in Punjab state.

The National Project on Aquifer Management (NAQUIM) aims to identify and map aquifers at high spatial resolution in order to better quantify the available groundwater resources in India (Saha et al., 2018). The NAQUIM project is currently developing groundwater management plans at district and block levels, primarily focussed on (a) reduction in groundwater abstraction via changes in cropping patterns, (b) artificial recharge and rainwater harvesting, and (c) development of channelized irrigation systems. Our previous work (van Dijk et al., 2016a) as well as the results presented in this paper have provided insights in terms of characterising spatio-temporal variations in groundwater level with aquifer heterogeneity and linking this to surface geomorphology. This framework can therefore be used to design location-specific groundwater resource management policies for the hotspots of groundwater depletion identified here, in particular focussing at a district level. These policies could usefully draw upon the complementary knowledge of the abundance and thickness of aquifer bodies in the subsurface, either observed directly (van Dijk et al., 2016a) or estimated by spatial correlation (van Dijk et al., 2016b), and groundwater recharge. For example, the option of artificial recharge can be guided by the geomorphic setting, which is easier to map and is strongly linked to subsurface stratigraphy as demonstrated by our study.

For example, for the districts of Ludhiana and Sangrur, we see a striking similarity between high tube well densities (Table S2; Fig. 12a-b) and abstraction rates (Fig. 13), suggesting that agriculture is the most significant causal factor for the severe groundwater losses in these districts. The CGWB (2011a & 2014a) documented groundwater abstraction of 4.87 billion m^3 (bcm) in 2009 and 4.89 bcm in 2011 in Sangrur district, which is likely a result of the high tube well density in this district (MoWR, 2007). Therefore, reducing irrigation water demand must be a high priority in these districts to improve the groundwater situation (option (a) of the NAQUIM). Recent modeling efforts have also shown that about 20% reduction in groundwater abstraction in this region can decrease the rate of water level decline by 36–67% in many districts (Shekhar et al., 2020). At the same time, the location of these districts in the central part of the Sutlej fan, with thick and abundant aquifer bodies in the subsurface (Fig. 15) (van Dijk et al., 2016a), means that managed aquifer recharge or groundwater banking (option b) is also feasible. By contrast, several districts in the eastern part of the study area, such as Karnal (Fig. 12b and 13), have moderate well densities but low abstraction values, and as a result, they show a lower decline in groundwater level. The southern and southwestern parts of the study area also show high EC values (Fig. 11), suggesting saline groundwater at shallow levels and thereby limiting its exploitation for agriculture. Artificial recharge schemes in these areas would be counter-productive, and would in any event suffer from low efficiency due to the limited amounts of aquifer material in the subsurface (Fig. 15); instead, rainwater harvesting combined with the development of channelised irrigation systems may be a good option in such areas. Our results are also of immense importance to promote community-driven efforts for regulating the groundwater extraction as well as implementing managed aquifer recharge efforts, as attempted in western India with good results (Patel et al., 2020). The emerging concept of groundwater sustainability in the Anthropocene also advocates maintaining ‘dynamically stable storage and flows’ using effective governance and management strategies (Gleeson et al., 2010).

Finally, our demonstration of the importance of the depositional setting and large-scale sedimentary architecture of the aquifer system as a key factor in governing patterns of groundwater level change offers a new approach to guiding groundwater management across the Indo-Gangetic Basin. Because the geomorphology of surface sediment routing systems is a good proxy for understanding subsurface stratigraphy and heterogeneity of the alluvial aquifer system (Harvey et al., 2005; Elshall et al., 2013; van Dijk et al., 2016a), it can provide a spatial framework for anticipating future patterns of groundwater depletion, even in areas that lack sufficient subsurface data (van Dijk et al., 2016b). This approach may also prove valuable in other regions of the world where irrigation is underpinned by abstraction from alluvial aquifers.

6. Conclusions

Our study of long-term and high-resolution records of groundwater level data from northwest India reveals that there are distinct patterns of groundwater level change for the periods 1974–2001 and 2002–2010. We find that groundwater level changes have not been uniform across the study area but were instead highly localized and structured. There is substantial spatial and temporal heterogeneity in groundwater levels, with declining, rising and relatively stable groundwater level trends observed in specific parts of the study area. While groundwater levels show a mixed trend between 1974 and 2001, most wells show a declining trend during 2002–2010. Our results suggest that between 1974 and 2010, groundwater levels declined at an average rate of -1.47 ± 0.02 cm/year during the pre-monsoon period, producing a total loss in groundwater storage of -36.01 ± 0.37 km^3, and at an average rate of -1.31 ± 0.02 cm/year during the post-monsoon period, producing a total loss of -32.03 ± 0.37 km^3. Most of this decline occurred in 2002–2010 as large parts of the study area showed a rapid decline after 2000. Areas of coherent groundwater level change are highly spatially correlated, with lateral dimensions of several tens of kilometers. We find a first-order correspondence between changes in groundwater level and available district-level data on both tube well density and abstraction volume, and the increased decline in water levels from 2002 may correlate with a shift from low-horsepower surface pumps to submersible pumps capable of extracting water from deeper levels. However, these relationships are not consistently observed across the entire study area, and abstraction alone cannot explain the spatial variability in groundwater levels across the region.

The spatial and temporal pattern of groundwater level changes can also be correlated with the geological heterogeneity of the aquifer system, which in turn depends upon the depositional architecture of the alluvial stratigraphy that underlies the region. This architecture comprises large fluvial fans and an intervening interfan area, and defines the subsurface abundance, dimensions, and distribution of sandy aquifer bodies in the study area. The proximal and medial fan areas, which are characterized by abundant aquifer material and thick sand bodies, have experienced more rapid groundwater level decline after 2000 compared to the interfan areas and distal fan areas where aquifer material is less abundant in the subsurface. We also find marked depletion along the Ghaggar-Hakra paleochannel, which may be due to a ‘first occupation’ effect and limited lateral extent of the thick and abundant aquifer bodies below the paleochannel. Similarly, marked groundwater lowering is associated with the trace of the incised valley of the Yamuna River. The presence of large pockets of saline groundwater in southwestern Punjab and southern Haryana also likely contributes to the heterogeneities in groundwater level change, as groundwater in these areas is largely unsuitable for irrigation and is thus subject to less intense abstraction.

The groundwater system in northwestern India is heavily stressed and the understanding of spatial inhomogeneities in groundwater depletion and its forcing mechanisms, as presented in this paper, is an important ingredient for designing a sustainable groundwater management strategy for this region. Our results provide some guidance for identifying local zones of major groundwater stress in this region that require detailed monitoring of groundwater level changes and which may also require domain-specific intervention strategies for sustainable groundwater management.

CRediT authorship contribution statement

Suneel Kumar Joshi: Formal analysis, Investigation, Writing - review & editing, Visualization. **Sanjeev Gupta:** Conceptualization, Writing - review & editing, Methodology. **Rajiv Sinha:** Conceptualization, Writing - review & editing, Supervision, Methodology, Project administration, Funding acquisition. **Alexander Logan Densmore:** Conceptualization, Writing - review & editing, Methodology, Project administration, Funding acquisition. **Shive Prakash Rai:** Writing - review & editing. **Shashank Shekhar:** Writing - review & editing. **Philippa J. Mason:** Writing - review & editing. **W.M. van Dijk:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2021.126492.

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